REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1. REPORT DATE *(DD-MM-YYYY)*	2. REPORT TYPE	3. DATES COVERED
	Conference Proceeding	10-14 June 2002

4. TITLE AND SUBTITLE

High Fidelity Simulations of Littoral Environments

5a. CONTRACT NUMBER

5b. GRANT NUMBER

5c. PROGRAM ELEMENT NUMBER
603755D

5d. PROJECT NUMBER

5e. TASK NUMBER

5f. WORK UNIT NUMBER

6. AUTHOR(S)

Richard Allard, Charlie N. Barron, Cheryl Ann Blain, Patrick J. Hogan, Timothy R. Keen, Lucy F. Smedstad, Alan J. Wallcraft, Charlie Berger, Stacy Howington, Jane Smith, Richard Signell, Matthew Bettencourt and Mark Cobb

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
Naval Research Laboratory
Oceanography Division
Stennis Space Center, MS 39529-5004

8. PERFORMING ORGANIZATION REPORT NUMBER
NRL/PP/7320-02-0007

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)
Office of Naval Research
800 N. Quincy St.
Arlington , VA 22217-5660

10. SPONSOR/MONITOR'S ACRONYM(S)
ONR

11. SPONSOR/MONITOR'S REPORT NUMBER(S)

12. DISTRIBUTION/AILABILITY STATEMENT

Approved for public release; distribution is unlimited

13. SUPPLEMENTARY NOTES

14. ABSTRACT

The littorals of the World are areas of great strategic importance. Approximately 95% of the world's population lives within 600 miles of sea, 80% of all countries border the coast and 80% of the world's capitals lie within 300 nautical miles of shore. With the end of the cold war, DoD' s focus has shifted from a large land/sea battle scenario with a monolithic global adversary to dealing with low-intensity conflicts in the near-coastal or littoral regions. In wartime, the ability to dominate the littoral, including the undersea environment, allows operating with impunity in the face of area denial threats while taking initial action to defeat those threats and prepare the battlespace for follow-on forces.

Information superiority - understanding and exploitation of the natural environment -- is critical to safe and effective operation of joint forces engaged in littoral expeditionary warfare. The tactical advantage will probably depend not on who has the most expensive, sophisticated platforms - but rather in who can most fully exploit the natural advantages gained by a thorough understanding of the physical environment. Every aspect of the littoral environment is of critical import to conducting military operations, a huge challenge to both the warfighters and the Meteorology and Oceanography (METOC) community that supports them.

15. SUBJECT TERMS
DoD's, monolithic global adversary, littoral region

16. SECURITY CLASSIFICATION OF: a. REPORT	b. ABSTRACT	c. THIS PAGE	17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
					Rick Allard
					19b. TELEPHONE NUMBER *(Include area code)*
Unclassified	Unclassified	Unclassified	SAR	15	228-688-4894

PUBLICATION OR PRESENTATION RELEASE REQUEST

Pubkey: 3296 NRLINST 5600.2

1. REFERENCES AND ENCLOSURES	2. TYPE OF PUBLICATION OR PRESENTATION		3. ADMINISTRATIVE INFORMATION
Ref: (a) NRL Instruction 5600.2 (b) NRL Instruction 5510.40D Encl: (1) Two copies of subject paper (or abstract)	( ) Abstract only, published ( ) Book ( ) Conference Proceedings (refereed) ( ) Invited speaker ( ) Journal article (refereed) ( ) Oral Presentation, published ( ) Other, explain	( ) Abstract only, not published ( ) Book chapter (X) Conference Proceedings (not refereed) ( ) Multimedia report ( ) Journal article (not refereed) ( ) Oral Presentation, not published	STRN NRL/PP/7320-02-7 Route Sheet No. 7320/ Job Order No. Classification X U ___ C Sponsor approval obtained X yes ___ no

4. AUTHOR

Title of Paper or Presentation

High Fidelity Simulations of Littoral Environments

Author(s) Name(s) (*First,MI,Last*), *Code, Affiliation if not NRL*

Richard A. Allard, Charlie N. Barron, Cheryl Ann Blain, Patrick J. Hogan, Timothy R Keen, Lucy F. Smedstad, Alan J. Wallcraft, Charlie Berger, Stacy Howington, Jane Smith, Richard Signell, Matthew Bettencourt, Mark Cobb

It is intended to offer this paper to the **2002 HPC User's Group Conference**
(*Name of Conference*)

10-JUN - 14-JUN-2002, Austin, TX, Unclassified
(*Date, Place and Classification of Conference*)

and/or for publication in **2002 HPC User's Group Conference, Unclassified**
(*Name and Classification of Publication*) (*Name of Publisher*)

After presentation or publication, pertinent publication/presentation data will be entered in the publications data base, in accordance with reference (a).
It is the opinion of the author that the subject paper (is ____) (is not X) classified, in accordance with reference (b).
This paper does not violate any disclosure of trade secrets or suggestions of outside individuals or concerns which have been communicated to the Laboratory in confidence. This paper (does ____) (does not X) contain any militarily critical technology.
This subject paper (has ____) (has never X) been incorporated in an official NRL Report.

Richard A. Allard, 7322 Richard Allard
Name and Code (*Principal Author*) (Signature)

5. ROUTING/APPROVAL

CODE	SIGNATURE	DATE	COMMENTS
Author(s) Allard	Richard Allard	6-5-02	
Section Head Preller	Ruth H Preller	6-6-02	
Branch Head **John M. Harding, 7320**	John Harding	6/7/02	
Division Head **William J. Jobst, 7300**	WJobst	6/7/02	1. Release of this paper is approved. 2. To the best knowledge of this Division, the subject matter of this paper (has ____) (has never X) been classified.
Security, Code **7030.1**	David R Calderon	6/11	1. Paper or abstract was released. 2. ~~A copy is filed in this office.~~ SSC-257-02
Office of Counsel, Code **1008.3**		6/14/02	Memo 77 6/6/02
ADOR/Director NCST **E.O. Hartwig, 7000**			
Public Affairs (*Unclassified/ Unlimited Only*), Code **7030.4**	Becky Rolando	6/11/02	Changes one reference
Division, Code			
Author, Code			

HQ-NRL 5511/6 (Rev. 12-98) (e) THIS FORM CANCELS AND SUPERSEDES ALL PREVIOUS VERSIONS

☒ A - Approved for public release, distribution is unlimited.

☐ B - Distribution authorized to U.S. Government agencies only *(check reason below):*

☐ Foreign Government Information ☐ Contractor Performance Evaluation ☐ Critical Technology

☐ Proprietary Information ☐ Administrative/Operational Use ☐ Premature Dissemination

☐ Test and Evaluation ☐ Software Documentation ☐ Cite "Specific Authority ____________________"

(Identification of valid documented authority)

Date statement applied ____________

Other requests for this document shall be referred to ________________________

(Insert Controlling DOD Office)*

☐ C - Distribution authorized to U.S. Government agencies and their contractors *(check reason below):*

☐ Foreign Government Information ☐ Software Documentation

☐ Administrative/Operational Use ☐ Critical Technology ☐ Cite "Specific Authority ____________________"

(Identification of valid documented authority)

Date statement applied ____________

Other requests for this document shall be referred to ________________________

(Insert Controlling DOD Office)*

☐ D - Distribution authorized to DOD and DOD contractors only *(check reason below):*

☐ Foreign Government Information ☐ Critical Technology

☐ Software Documentation ☐ Cite "Specific Authority ____________________"

(Identification of valid documented authority)

☐ Administrative/Operational Use

Date statement applied ____________

Other requests for this document shall be referred to ________________________

(Insert Controlling DOD Office)*

☐ E - Distribution authorized to DOD components only *(check reason below):*

☐ Proprietary Information ☐ Premature Dissemination ☐ Critical Technology

☐ Foreign Government Information ☐ Software Documentation ☐ Direct Military Support

☐ Administrative/Operational Use ☐ Contractor Performance Evaluation ☐ Test and Evaluation

Date statement applied ____________ ☐ Cite "Specific Authority ____________________"

(Identification of valid documented authority)

Other requests for this document shall be referred to ________________________

(Insert Controlling DOD Office)*

☐ F - Further dissemination only as directed by ____

(Insert Controlling DOD Office)*

Date statement applied ____________ or higher DOD authority ________________________

☐ G - Distribution authorized to U.S. Government agencies and private individuals or enterprises eligible to obtain export-controlled technical data in accordance with regulations implementing 10 U.S.C. 140c.

Date statement applied ____________

Other requests for this document shall be referred to ________________________

(Insert Controlling DOD Office)*

*For NRL publications, this is usually the Commanding Officer, Naval Research Laboratory, Washington, DC 20375-5320

7. OTHER LIMITATION

☐ Classification ☐ NOFORN ☐ DTIC exempt (explain) ____________________

____
Classification Review
(initial/Date)

Substantive changes made in this document after approval by Classification Review and Public Release invalidate these reviews. Therefore, if any substantive changes are made by the author, Technical Information, or anyone else, the document must be returned for another Classification Review and Publication Release.

8. INSTRUCTIONS

Author completes and submits this form with the manuscript via line channels to the division head for review and approval according to the routing in Section 4.

1. NRL Reports..Submit the diskette (if available), manuscript, typed double-spaced, complete with tables, illustrations, references, draft SF 298, and proposed distribution list.
2. NRL Memorandum Reports..Submit a copy of the original, typed manuscript complete with tables, illustrations, references, draft SF 298, and proposed distribution list.
3. NRL Publications or other books, brochures, pamphlets, proceedings, or any other printed publications..........................Handled on a per case basis by Site Technical Information Office.

Department of Defense High Performance Computing Modernization Program

USERS GROUP CONFERENCE 2002

Tuesday, May 20, 2003 10:07:59 AM

Tuesday

Wednesday

Thursday

About Austin, TX

About The University of Texas at Austin

UGC2002 - AUSTIN, TEXAS - JUNE 10-14, 2002

Hosted by ERDC MSRC (Click here for more information)

hpcmo msrc dc dren chssl questions search

Last modified June 20, 2002.

High Fidelity Simulations of Littoral Environments

Richard Allard[1], Charlie Barron[1], Cheryl Ann Blain[1], Patrick Hogan[1], Timothy Keen[1], Lucy Smedstad[1], Alan Wallcraft[1], Charlie Berger[2], Stacy Howington[2], Jane Smith[2], Richard Signell[3], Matthew Bettencourt[4] and Mark Cobb[5]

[1]Naval Research Laboratory, Stennis Space Center, MS
[2]Engineering Research and Development Center, Vicksburg, MS
[3]NATO/SACLANT Undersea Research Centre, La Spezia, Italy
[4]Center for Higher Learning/University of Southern Mississippi, Stennis Space Center, MS
[5]Sverdup Technology Inc., Stennis Space Center, MS

INTRODUCTION

The littorals of the World are areas of great strategic importance. Approximately 95% of the world's population lives within 600 miles of sea, 80% of all countries border the coast and 80% of the world's capitals lie within 300 nautical miles of shore. With the end of the cold war, DoD's focus has shifted from a large land/sea battle scenario with a monolithic global adversary to dealing with low-intensity conflicts in the near-coastal or littoral regions. In wartime, the ability to dominate the littoral, including the undersea environment, allows operating with impunity in the face of area denial threats while taking initial action to defeat those threats and prepare the battlespace for follow-on forces.

Information superiority – understanding and exploitation of the natural environment -- is critical to safe and effective operation of joint forces engaged in littoral expeditionary warfare. The tactical advantage will probably depend not on who has the most expensive, sophisticated platforms .- but rather in who can most fully exploit the natural advantages gained by a thorough understanding of the physical environment. Every aspect of the littoral environment is of critical import to conducting military operations, a huge challenge to both the warfighters and the Meteorology and Oceanography (METOC) community that supports them.

Characterization of the battlespace environment to ensure optimal employment of personnel, systems and platforms depends on continuous improvement in science and technology toward that aim. Key and essential elements in that characterization are effective, relocatable, high-resolution, dynamically linked mesoscale, meteorological, coastal oceanographic, surface water/groundwater, riverine/estuarine and sediment transport models. The linkages between these models, coupled with the complexity and the scale of the environment, require the implementation of focused sets of these models on DoD High Performance Computing (HPC) architectures in support of real time operations, scenario (operational and/or training) planning, and coarse of action analysis. Figure 1 shows the wide range of physical processes that occur in littoral waters.

The High Fidelity Simulations of Littoral Environments (HFSoLE) Portfolio is funded by CHSSI under the HPCMO. The HFSoLE effort is broken into four projects. 1) The System Integration and Simulation Framework Project is developing the interface algorithms for the atmospheric, riverine, estuarine, wave, tidal and ocean models in this portfolio. 2) The Near-shore and Estuarine Environments Project is coupling and enhancing nearshore process models to efficiently simulate interactions between winds, waves, currents, water levels, and sediment transport. 3) The Surface Water/ Groundwater, Riverine and Tidal Environments Project is enhancing the capabilities of the Adaptive Hydraulics (ADH) model. This project is working toward providing DoD the tools to generate fast and accurate estimates of water depths and velocity distributions for use in ingress/egress assessment for rivers and streams, flow rate and sediment loading as input for coastal simulation, and ground-surface inundation and moisture

content predictions for use in local atmospheric simulations. 4) The System Applications Project is improving the fidelity and execution speed of DoD maritime operation simulation systems dependent on data from ocean surface behavior models. Such simulations include amphibious assault, mine clearing and sea keeping operations. This project provides for the development, implementation and testing of an environmental server to support Modeling & Simulation (M&S).

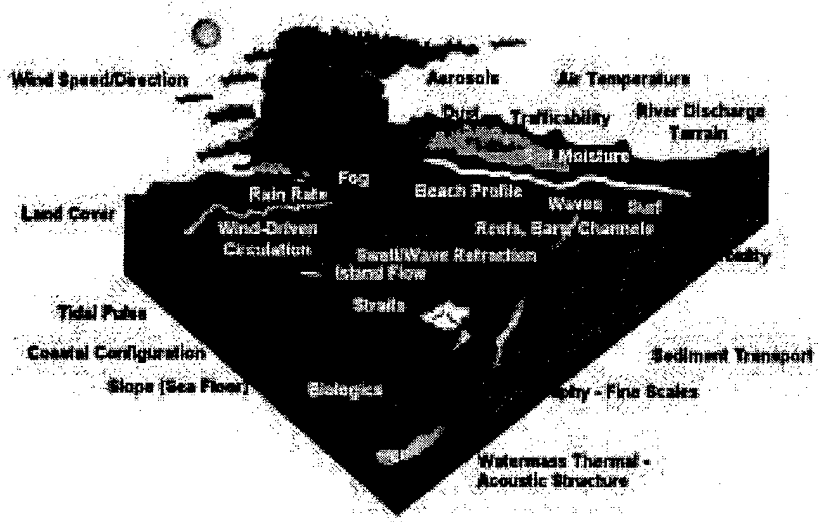

Figure 1. Physical processes that occur in littoral waters include wind forcing, tides, waves, ocean circulation and sediment transport.

Models And Applications

The following section presents an overview of the ocean circulation, nearshore process, and surface water/groundwater models contained in HFSoLE. Grand challenge time was utilized in performing model simulations with the goal to support DoD efforts.

HYCOM

A series of ocean circulation simulations in the Japan/East Sea have been performed on the Cray T3E (NAVO MSRC) under the HPC HFSoLE Grand Challenge Project. The model used is the Hybrid Coordinate Ocean Model (HYCOM), a next generation circulation model under development at the Naval Research Laboratory. Ideally, an ocean general circulation model should (a) retain its water mass characteristics for centuries (a characteristic of isopycnal coordinates), (b) have high vertical resolution in the surface mixed layer (a characteristic of z-level coordinates), and (c) have high vertical resolution in surface and bottom boundary layers in coastal regions (a characteristic of terrain-following coordinates). Hence, HYCOM is designed to be isopycnal in the open, stratified ocean, but makes a dynamically smooth transition to a terrain-following coordinate in shallow coastal regions, and to z-level coordinates in the mixed layer and unstratified seas.

The Japan/East Sea has been used to test the robustness of HYCOM because it contains many circulation features found in the global ocean, such as a western boundary current, subpolar gyre, and rich eddy field, and it is small enough to allow simulations with very high resolution. Under this grand Challenge Project, simulations with 3.5 km horizontal resolution were

performed. Scalability was via MPI/SHMEM, or OpenMP, or both, although SHMEM was used exclusively for the simulations performed on the T3E. The mesh size for the high-resolution configuration is 394x618x15, and a one-year simulation requires about 12,000 CPU hours per model year.

High horizontal grid resolutions are needed to adequately resolve the mesoscale features as well as the coastline and bottom topography, especially over the shelf. The impact of progressively increasing the grid resolution is shown in Figure 2. At 14 km resolution, unrealistic overshot of the East Korean Warm Current (140 °E, 39 °N) is significant. This overshoot is diminished at 7.5 km, and at 3.5 km the current separates from the coast at the observed latitude. Also, the strength of the subpolar gyre strengthens as the horizontal resolution is increased. Simulations with the Navy Layered Ocean Model (NLOM) suggest that these changes in surface circulation are due to interaction with abyssal currents that are influenced by the bottom topography. The same mechanism appears to be dominant here, but further analysis is needed to be sure.

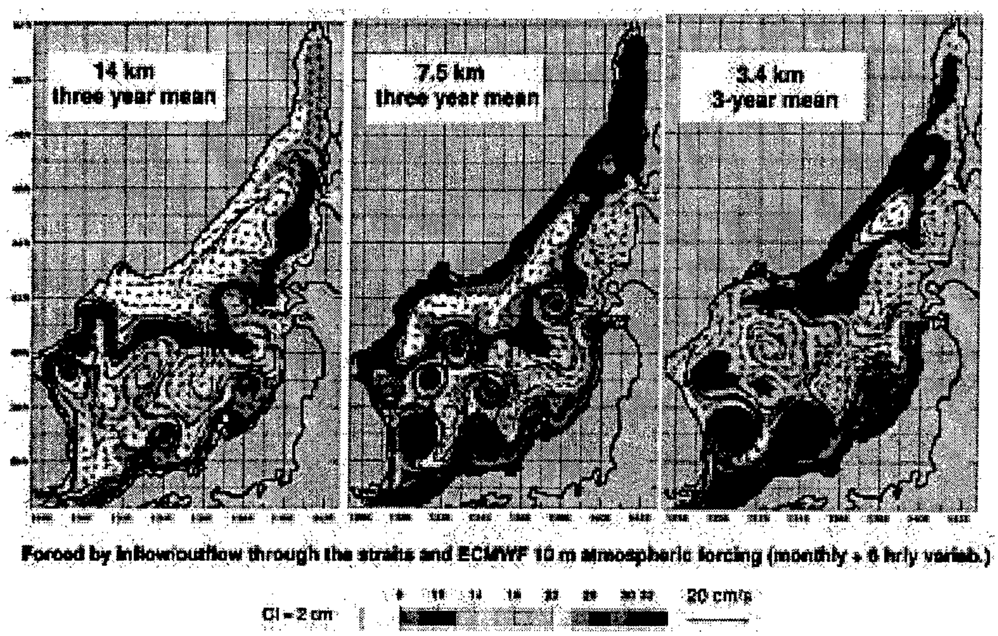

Figure 2. Impact of increasing the horizontal resolution of the HYCOM model in the Japan/East Sea.

NCOM

Coastal regions will be included in the Navy Coastal Ocean Model (NCOM)-based global nowcast/forecast system which will serve as a complementary model in the Hybrid Coordinate Ocean Model (HYCOM)-based global nowcast/forecast system. Global NCOM employs a sigma-z coordinate system (Martin, 2000) in a fully global domain including the Arctic and continental shelves. This will provide high vertical resolution in coastal regions while maintaining a specified minimum vertical resolution in the deep ocean with a non-uniform distribution of levels to maintain higher near-surface resolution(Hurlburt, Barron, and Wallcraft, personal communication).

Global NCOM has 1/8° resolution at mid-latitudes in a 2048x1280x41 curvilinear sigma-z grid with 19 sigma levels and maximum surface level thickness of 1m (Martin, 2000). It is

forced by the Navy Operational Global Atmospheric Prediction System (NOGAPS 4.0) (Hogan and Rosmond, 1991) from Fleet Numerical Meteorology and Oceanography Center (FNMOC). Daily 2-D and 3-D temperature and salinity fields produced by the Modular Ocean Data Assimilation System (MODAS) (Fox et al, 2002) at the Naval Oceanographic Office are assimilated. MODAS uses climatological correlations between steric surface height (SSH) deviation, surface temperature (SST) deviation and subsurface temperature deviation to predict 3-d temperature fields from surface information. SST from the operational MODAS2D analysis of satellite SST and SSH from the operational, altimetry-assimilating 1/16° NLOM (Wallcraft, 1991) provide input for the 3D MODAS calculations. MODAS routines analyze the NCOM temperature fields to determine mixed layer depth, which is defined as the depth (if any) at which temperature drops to 0.25 °C below the surface temperature (Rhodes et al., 2002).

1/8° global NCOM model simulations have been performed on the NAVO IBM-SP on 128 processors (32 nodes) with a wallclock limit of two hours. Each model simulation corresponds to 10 model days. This can be performed in reanalysis mode, hindcast mode, or a daily mode consisting of a hindcast of three to five days, an analysis, and then a forecast of three days. Figure 3 depicts a recent Global NCOM sea surface temperature analysis.

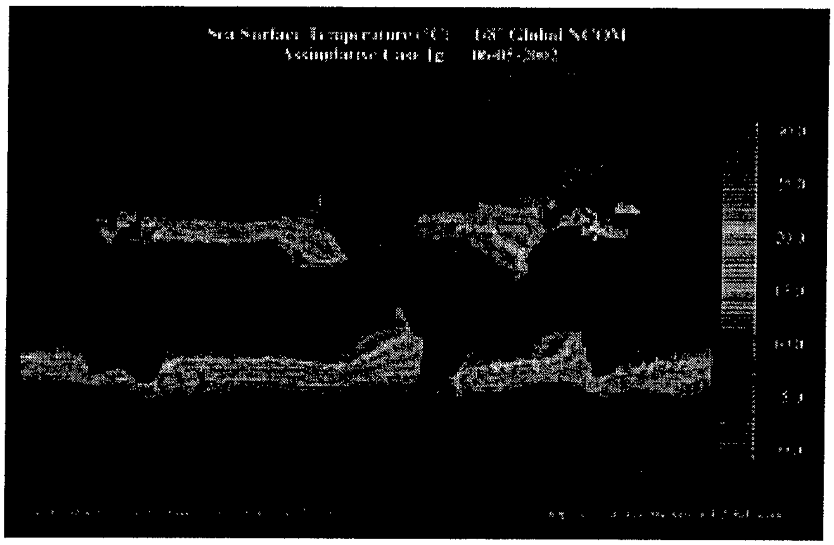

Figure 3. NCOM sea surface temperature analysis for June 5, 2002.

STWAVE

Ocean waves near the coast have a huge impact on military activities aimed at getting soldiers, sailors, marines, and equipment on the shore. Although waves are generated in the open ocean and propagate over long distances, the last kilometer or less near the shore is the critical region for landing and docking. Nearshore wave transformation is solved in the model STWAVE (Smith, 2002) using the wave action balance equation. The model includes the processes of shoaling and refraction (increases in wave height and changes in wave direction in shallow water), wave-current interaction (changes in wave properties caused by tidal or nearshore currents), wave growth due to the wind, and wave breaking. The model is based on linear wave theory and does not include reflection or bottom friction. By linking the nearshore wave transformation model STWAVE with deepwater wave forecasts or hindcasts (at large spatial scales), nearshore waves can be estimated on beaches and at harbor and inlet entrances. Forecasts

are used for short-term planning of operations and hindcasts are used to garner climatologically information for longer-term planning (typical and extreme conditions, seasonal variation, storm probability).

Nearshore wave transformation modeling in the past has been run on HPC platforms to make forecasts to support war fighters. To meet stringent time requirements for producing forecasts, the model was run with very coarse spatial resolution and less frequency in time than is optimal. Under the CHSSI HFSoLE project, STWAVE was parallelized to exploit HPC capabilities. Tests earlier this year demonstrated that the parallel version of STWAVE was over 90 percent efficient using 32 processors on both the Cray T3E and SGI Origin 3000. This translates into increasing the model through-put by a factor of 28. The highly efficient parallelization allows improved resolution of the nearshore domain (which improves model accuracy) and more frequent model runs (more resolution in time), while still meeting or beating required forecast time constraints. Improved nearshore modeling times also allows more time for other modeling components and for decision making. Figure 4 shows verification of the parallel version of STWAVE at Duck, NC, for the year 1997. The agreement with field measurements is excellent. Full-year simulations were not run prior to the parallel capability.

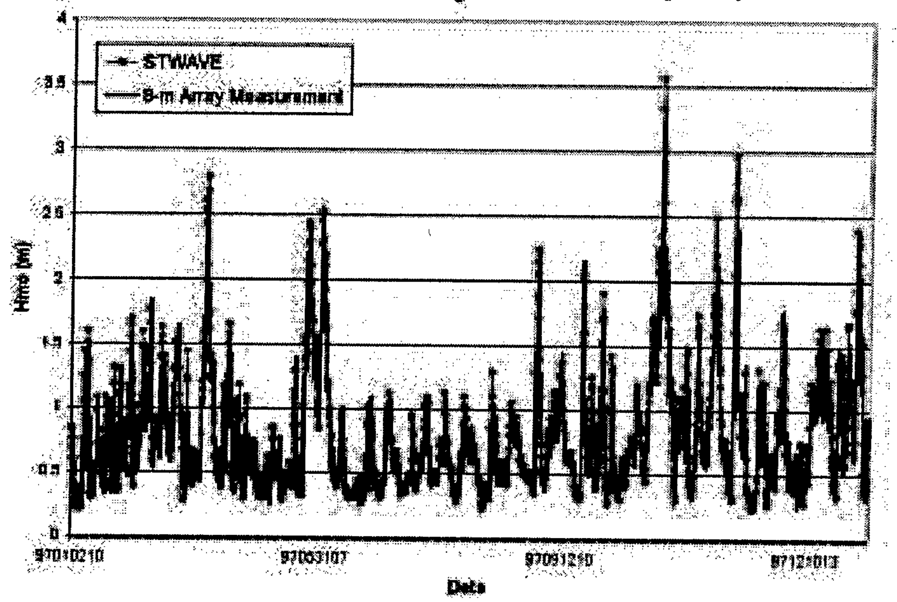

Figure 4. Verification of parallel version of STWAVE wave heights at Duck, North Carolina versus observational data for a one year period.

Continuing challenges in the work include expanding to more HPC platforms and a larger number of processors, implementing additional improvements to model efficiency, and upgrading model physics. The CHSSI work will focus on interfacing STWAVE with circulation and sediment transport models to provide a greater understanding of the physical processes that impact directly on operations, equipment, and training. This work is partnered with the Naval Research Lab as well as with other ERDC researchers. This work falls within the Climate Weather Ocean CTA.

Adaptive Hydraulics Code (ADH)

The **AD**aptive **H**ydraulics (ADH) code is a finite element model constructed within the Department of Defense (DoD). ADH is designed to address a host of water related problems, including resource protection and flow and constituent transport quantification. In this example

the shallow water equations are being used. These are the typical equation sets used for flow in rivers and tidal regions. The code uses a discrete Newton approach to develop the algebraic equation set. The resulting linear system is solved using the BiCG-Stab iterative solver. Preconditioners are essential to make efficient computations. Domain decompostion preconditioners presently in ADH are, Jacobi, 1-level Additive Schwarz, 2-level Additive Schwarz, and a 2-level hybrid scheme. The domain is broken into many blocks. The 2-level preconditioner then performs two direct solves on this aggregate of blocks. The first is a "fine solve" on each individual block, this is followed by a "coarse solve" over the entire domain but with resulting factors representing "average" results per block. The selection of an optimum number of blocks for a variety of numbers of processors can be daunting. In prior work, the total number of blocks resulting in near optimum timings appeared to be relatively constant over a wide range of numbers of processors. A series of simulations have been performed in which many numbers of blocks and processors were chosen to try to determine if this is true. Runs were made on the ERDC Origin O3K and on the ERDC Cray T3E. The results for the O3K are shown in Figure 5. The investigation used 2, 4, 8, and 16 processors and up to a total of 200 blocks. The timings are nondimensional ratios of the best time in the entire experiment. Strictly speaking the optimum total number of blocks is shown not to be a constant. However, if the optimum is based upon the larger number of processors, around 80 blocks, the times on the other processors would be reasonable. The results are not terribly sensitive except for the lowest number of processors, 2, in which a time about 25% above optimum would be found. Generally speaking the total number of blocks required to reach an optimum decreases as the number of processors increases.

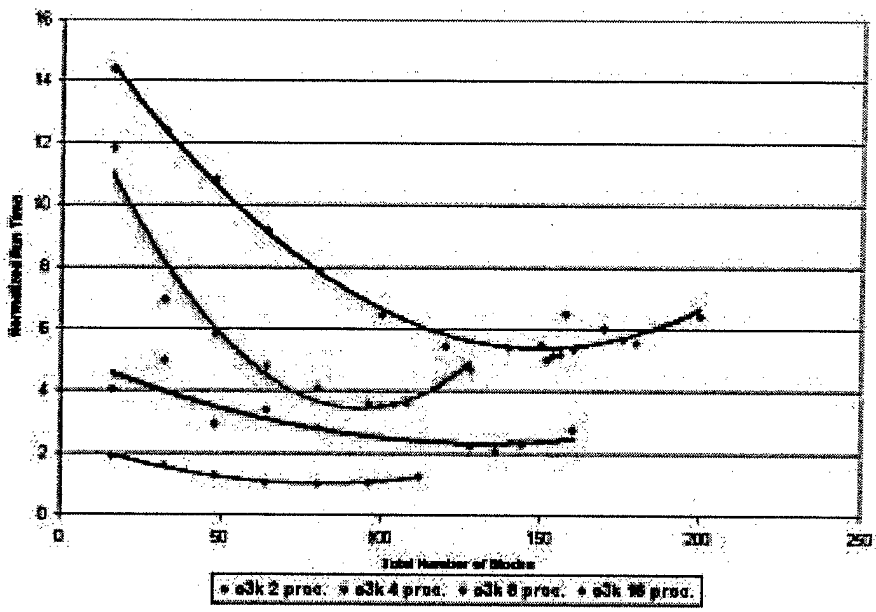

Figure 5. Total number of blocks versus run time for preconditioner in ADH. Timings based on 2, 4, 8, and 16 processors on the ERDC Origin 3000.

Littoral Sedimentation and Optics Model (LSOM)

The Littoral Sedimentation and Optics Model (LSOM) is a derivative of the TRANS98 model described by Keen and Glenn (1998) and Keen and Stavn (2000). The bottom boundary layer component is a modification of the wave-current interaction model of Glenn and Grant

(1987). It calculates the combined shear stresses resulting from wave and current interaction in the marine bottom boundary layer. The resuspension and optical properties of the sand and silt component are described by Keen and Stavn (2000). The LSOM model has been modified to simulate the resuspension of clay minerals following Gailani et al. (1996). The mass of sediment eroded from a cohesive bed is given by:

$$\varepsilon = \frac{a_o}{t_d^n}\left[\frac{\tau - \tau_o}{\tau_o}\right]^m$$

for $\tau > \tau_o$, where a_o is a site-specific constant, t_d is time in days since deposition, τ is the bottom shear stress, and the constants n and m depend on the depositional environment. For this study, we do not have sufficient data to calibrate this equation so we will use values suggested by Gailani et al. (1996). This is considered reasonable because the purpose of this study is to examine patterns of resuspension and the resulting optical properties. The clays are assumed to have a mean floc diameter of 10 microns. This is used in calculating their scattering coefficients.

The LSOM model is run independently of the hydrodynamic and wave models. It uses a time step of 3 hours. Sedimentation is simulated for the same interval as the other models, however.At every model cell, the sand component of the sediment is resuspended separately from the clay component and their optical characteristics are added to find the total scattering coefficients. The Diver Visibility DV is calculated from the biogenic and minerogenic scattering coefficients using the following relationship

$$DV = \frac{4.8}{(b_{chlor} + b_{minero})} \times \frac{A_s}{0.3048}$$

where b_{chlor} is the scattering due to chorophyll (biogenic particles), b_{minero} is the scattering due to resuspended mineral sediments, and A_s is the scattering albedo. The scattering due to organic particles is calculated from the surface chlorophyll concentration derived from the SeaWiFs sensor

$$b_{chlor} = 0.252C^{0.635}(0.635)(0.97)\left(\frac{660.}{532}\right)$$

where C is the chlorophyll concentration.

The model incorporates MPI processing in calculating transformation matrices for input waves, currents, bathymetry, and sediment type. It also uses MPI for the main computation loop, assigning blocks of grid rows to individual processors. An efficiency of 0.41 has been obtained with 12 processors on the Sun 10000E (wolfe) at NAVO.

Persian Gulf Studies

Contained within the region defined by the Persian Gulf, Strait of Hormuz and the Gulf of Oman is one of the busiest and most important shipping lanes in the world. A vessel passes through the Strait of Hormuz every 6 min and approximately 60% of the world's marine transport of oil comes from this region (Reynolds, 1993). For a region of such economic importance, comprehensive studies investigating the circulation of the region have been sparse, in part, due to the scarcity of observations.

The Persian Gulf is a semi-enclosed marginal sea located at the southeastern end of the Arabian Peninsula. Moving from the SW coast counterclockwise along the SE coast, Gulf waters are bordered by the United Arab Emirates, Qatar, Bahrain, Saudi Arabia, Kuwait, Iraq and Iran. Depths in the Arabian Gulf are quite shallow averaging approximately 50 m. Connection to the Gulf of Oman and the eastern Indian Ocean is through the Strait of Hormuz whose narrow constriction controls the tidal character of the basin, separating it from the Indian Ocean co-tidal system. The bathymetry of the Arabian Gulf is markedly asymmetrical about the NW-SE axis of

the basin. A deep channel off the Iranian coast contrasts the shallow broad shelf on the Arabian side of the Gulf.

The following section describes a series of models that are utilizing Challenge computational resources to study waves, tides and sediment transport in the Persian Gulf.

ADCIRC

The tide and storm surge computations in the Persian Gulf are made using the fully nonlinear, two-dimensional, barotropic hydrodynamic model ADCIRC-2DDI (Luettich et al., 1992). The ADCIRC model has an extensive and successful history of tidal prediction in coastal waters and marginal seas (e.g. Westerink et al., 1994; Blain et al., 1994; Luettich and Westerink, 1995; Blain, 1998; Fortunato, 1998; Luettich et al., 1999). The model is well suited to tidal studies because of its computational efficiency that is due in part to implementation of the finite element method, MPI parallelization of the code, and the use of an iterative sparse matrix solver. One advantage of the model for tidal analyses is the facility for timely and complete run-time harmonic decomposition for astronomical and nonlinear compound and over-tide components of the tidal signal. One can expect to complete simulations which extend from months to a year and employ 30 second time step increments expediently on both workstation and supercomputer platforms without unreasonable storage requirements. The ADCIRC model configuration for the Persian Gulf is similar to the operational model at NAVOCEANO described in Blain et al. (2002).

The ADCIRC-2DDI model is based on the well-known shallow water equations that are derived through a vertical integration over the water column of the three-dimensional mass and momentum balance equations subject to the hydrostatic assumption and the Boussinesq approximation. Though surface heating and evaporative fluxes together are known to be dominant mechanisms for inducing circulation in the Arabian Gulf (e.g. Chao et al, 1992), baroclinic processes are neglected here leaving only the tide and surge component of the circulation. Bottom stress terms are parameterized using the standard quadratic friction law and no lateral mixing due to diffusion or dispersion is considered. Numerical solution of the ADCIRC model governing equations is achieved by recasting the continuity equation into a generalized wave continuity equation (Lynch and Gray, 1979; Kinnmark, 1984). The discrete problem in space is approached through an application of the finite element method. The wetting and drying of computational elements is possible within ADCIRC-2DDI but is not activated for these computations.

The source of bathymetry used with the ADCIRC model is the DBDB-V 2 minute data base (Naval Oceanographic Office, 1997) on which a minimum depth of 3 m is imposed to eliminate drying of computational points along the shoreline. The model domain includes the Persian Gulf, Strait of Hormuz, and extends to approximately the 200 m isobath in the Gulf of Oman. The finite element mesh for this domain contains 17440 computational points whose spacing ranges from 0.5-1.0 km near the Shatt al Arab river inflow in the NW to 8 km in the Gulf of Oman.

Tidal forcing from 8 constituents (Q1, O1, K1, N2, M2, S2, K2, and P1) is applied both at the open boundary and internal to the domain through the tidal potential. Values for tidal constituents prescribed at the open boundary are obtained from results of the Grenoble global tide model (LeProvost et al., 1994). Wind velocities at 10-m over a 27 km resolution grid are obtained from the Navy's COAMPS (Hoder and Doyle, 1999) model. Wind stresses that serve as surface forcing for the ADCIRC model are then computed using the formulation of Garratt (1977). The bottom friction coefficient is uniform and set equal to 0.0015. Simulations are spun up from a homogeneous initial condition using a ramp in time equivalent to fifteen days. The model run extends 30 days beyond the spin-up period (i.e. June 1, 2001 to June 30, 2001) during which sea surface elevation and currents for all grid points are written every two hours. A time step of 30

seconds is more than sufficient to satisfy the Courant criterion over the entire domain. The ADCIRC model of the Persian Gulf ran on 4 processors of the IBM SP3 (375 MHz) in 3:20 hours. Figure 6 depicts ADCIRC water elevation and currents for June 1, 2001 at 00 GMT.

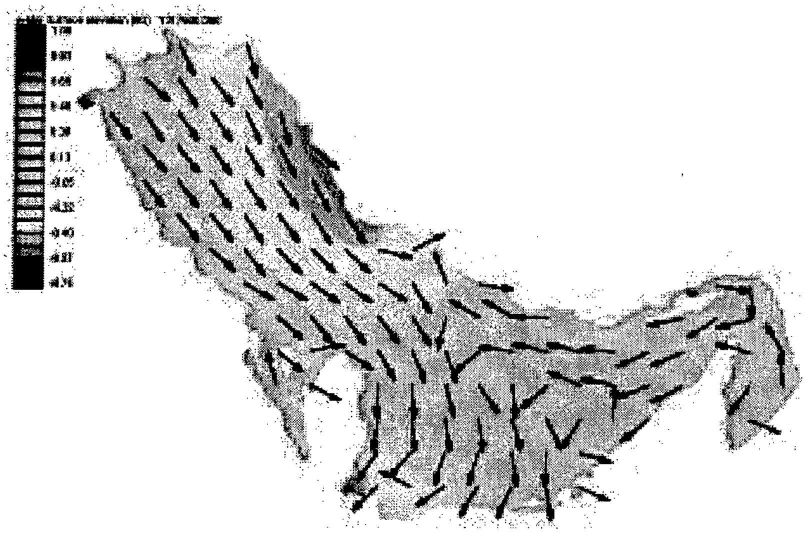

Figure 6. ADCIRC Arabian Gulf simulation results for June 1, 2001. Color shading indcates water elevation (m), arrows show direction of flow.

SWAN

A series of wave simulations were performed in the Persian Gulf using the OpenMP version of the Simulating Waves Nearshore (SWAN) wave model. The serial code for SWAN was parallelized by the Mississippi State University and NAVO MSRC Programming Environment and Training (PET) Office located at Stennis Space Center, MS. SWAN was originally a serial code that was considered unamenable to parallelization. Due to the data dependencies of the implicit technique, a straight forward domain decomposition of the spatial grid was not possible without completely altering the numerical algorithm. Instead, a shared memory pipelined parallel technique was adopted that would require no changes in numerical scheme or data layout. By introducing OpenMP directives at a fairly high level in the numerical scheme, the parallel version of SWAN runs with the same input and output files as the serial code.

SWAN (Booij et al, 1999) is based on the wave energy balance equation with source and sink terms. Boundary conditions were provided by directional wave spectra obtained by running a nested-version of the OpenMP deep-water WAM wave model. The WAM spectra were specified on the SWAN eastern boundary at four locations along 58.0 °E. SWAN was forced with COAMPS 10-m winds for two simulation periods: a) September 1-30, 2000 and b) June 1-30, 2001. The model was run in a non-stationary (time-dependant) mode with a 15-minute timestep. For these preliminary studies, tides were not considered. Figure 7 depicts the SWAN wave height and direction for June 1, 2001. Note the high waves in the northwest portion of the Persian Gulf due to strong wind forcing. Future work will investigate the use of ADCIRC tides as input to SWAN. Wave heights and directions from SWAN are used as input to the Littoral and Sedimentation Optics Model (LSOM) described in the next section.

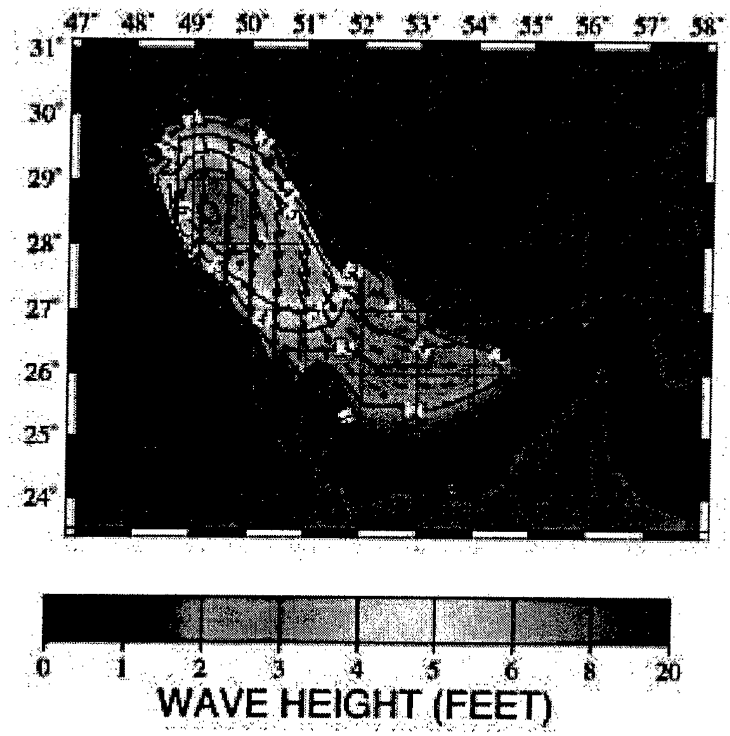

Figure 7. SWAN wave height (ft) for June 1, 2001 00 GMT. Arrows depict direction waves are moving toward.

LSOM

The bottom sediment in the Persian Gulf consists primarily of carbonate (calcite and aragonite) and evaporite sediments, including halite, gypsum, and anhydrite, which are found in the sabkha areas along the coast (Ross and Stoffers, 1978). Wind-blown terrigeneous sediments comprise less than one-third of the sediment within the area and river inflow is minimal. The majority of the sediment is silt and the sand component is generally less than 20%.

This study simulates resuspension of the sediments within the Persian Gulf using LSOM. The sedimentation model is run on a Cartesian grid with horizontal dimensions of 3262 m and 3702 m along the east-west and north-south axes, respectively. The bottom boundary layer is represented by 31 sigma levels, with 10 located within the wave boundary layer. The sediment within the Persian Gulf is represented by 20 size classes with a mean of 62 microns. The resulting predicted diver visibility will be compared to the value calculated directly from the satellite sensor (Figure 8a). Figure 8 shows the relationship between low diver visibility and resuspended sediment in shallow water near the coast, as predicted by LSOM (Figure 8b). Note the high visibility within the embayments to the north and south of the Qatar peninsula, as indicated by yellow hues in Figure 8a and blues in Figure 8b.

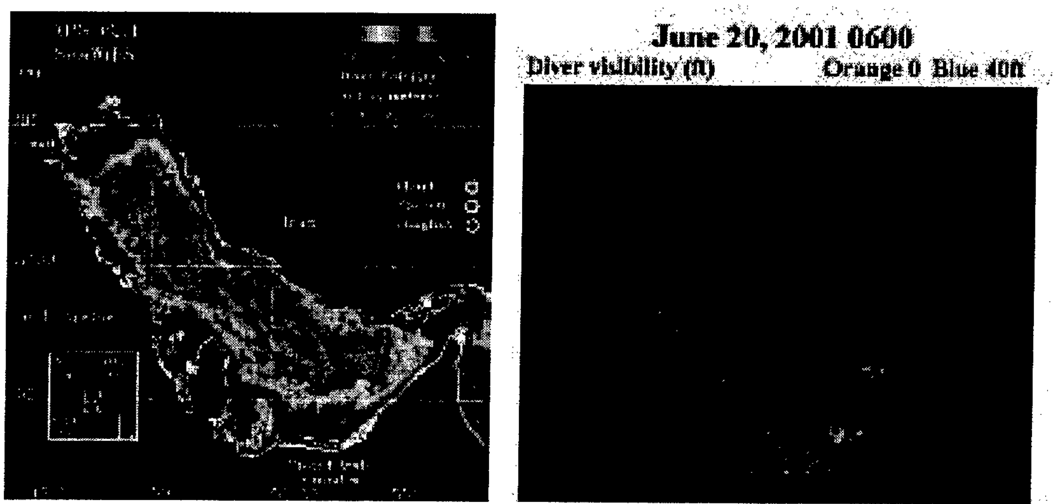

Figure 8. Diver visibility for the Persian Gulf on 20 June 2001: (a) computed from the SeaWiFS sensor and (b) calculated from LSOM using resuspended sediment and constant chlorophyll.

The model-predicted diver visibility for the second half of June 2001 (Figure 9) shows daily variability related to tides as well as larger changes associated with storms. The pattern of predicted visibility is correlated with wind waves generated within the Persian Gulf.

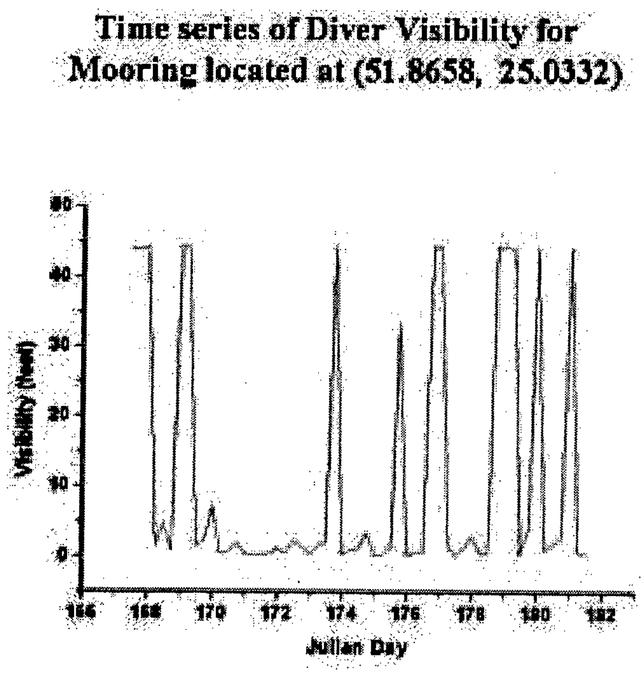

Figure 9. Time series of diver visibility predicted by LSOM for June 16-30, 2001. the station is located east of the Qatar Peninsula.

Adriatic Sea Studies

Researchers at NRL-Monterey, NRL-Stennis, and the NATO SACLANT Undersea Research Centre are using HPC resources to develop and study the performance of a high resolution coupled wind/current/wave/sediment coastal modeling system. The wind is provided by COAMPS, triple-nested with a 4 km resolution over the entire Adriatic. The ocean currents are computed by NCOM at a 2 km resolution. The waves are computed by SWAN on the same 2 km grid. The LSOM model will be driven using the currents and waves from NCOM and SWAN to provide simulations of sediment-related optical clarity for use such as diver visibility and lidar penetration. These models will be critically assessed during a large field program in the Adriatic Sea that will be carried out from Sep 2002-May 2003.

Figure 10 shows a snapshot of a typical "Bora", a frequent winter meteorological event where strong winds blow across the Northern Adriatic. The currents drive the fresh-water plume from the Po River down the coast, and also generate waves capable of resuspending sediments deposited near the Po River mouth.

A significant results so far is that higher-resolution nested wind modeling made possible by HPC resources has for the first time produced wave fields that compare well with observed buoy data without the application of any scale factors in this region. Previous lower resolution meteorological products had to be multiplied by factors of 1.3 or 1.5 before they produced acceptable results.

These models use the HPC systems as follows. The OpenMP version of SWAN is being used on the SGI Ruby (8-16 processors) under the HFSoLE Grand Challenge. NCOM, using MPI, is run typically with 16 nodes on the ERDC O3K (ruby). Both the NCOM and COAMPS runs were performed under the Coupled Mesoscale Modeling of the Atmosphere and Ocean (379) Grand Challenge.

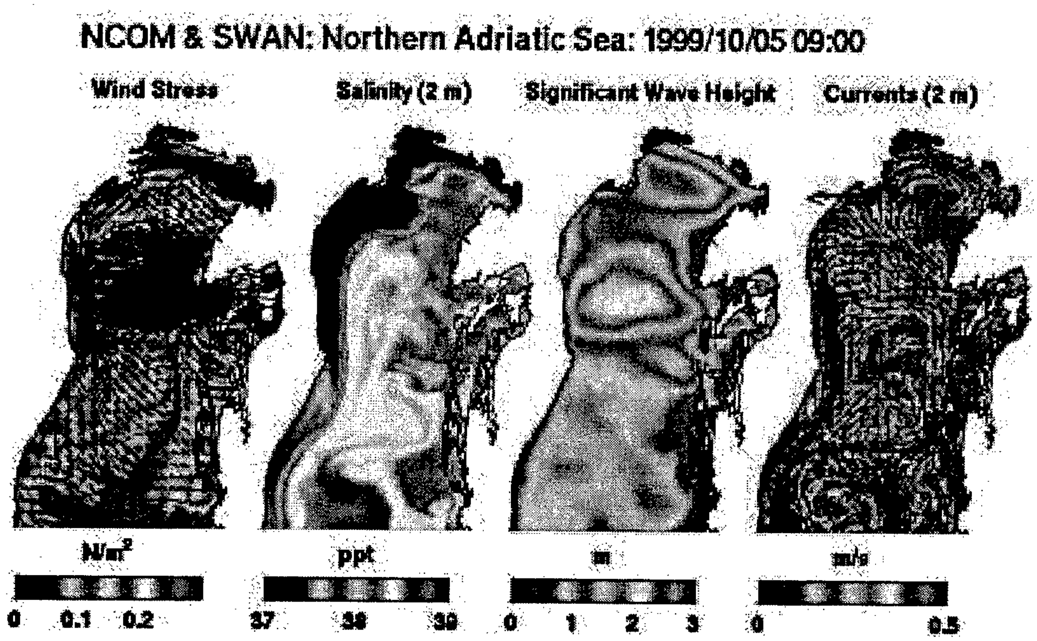

Figure 10. Snapshot of a "Bora" in the Northern Adriatic. a) COAMPS wind stress, b) NCOM salinity (PPT), c) SWAN wave height m), and d) NCOM 2-m currents (m/s).

Model Coupling Environmental Library (MCEL)

In the realm of geophysical modeling the current state-of-the-art models have the capability to run at very high spatial resolutions. This has led to a drastic increase in the accuracy of the physics being predicted. Due to the increased numerical accuracy, once neglected effects such as non-linear feedback between different physical processes can no longer be ignored. The ocean's deep water circulation, surface gravity waves and atmosphere above can no longer be treated as independent entities, and must be considered as a coupled system. One solution to this problem is to link models together through a series of surface variables. An example would be the evaporative cooling of the ocean, which at a simple level, requires the sea surface temperature, humidity and temperature of the atmosphere and in turn would return the mass and heat flux into the atmosphere.

Under the High Fidelity Simulation of Littoral Environments (HFSoLE) project the Model Coupling Environmental Library (MCEL) is under development. The MCEL infrastructure utilizes a data flow approach where coupling information is stored in a single server or multiple centralized servers and flows through processing routines called filters to the numerical models which represent the clients. These filters represent a level of abstraction for the physical or numerical processes which join together different numerical models. The extraction of the processes unique to model coupling into independent filters allows for code reuse for many different models. The communication between these objects is handled by the Common Object Request Broker Architecture (CORBA). In this paradigm the flow of information is fully controlled by the clients. Figure 11 represents a hypothetical example of how such a system might be used.

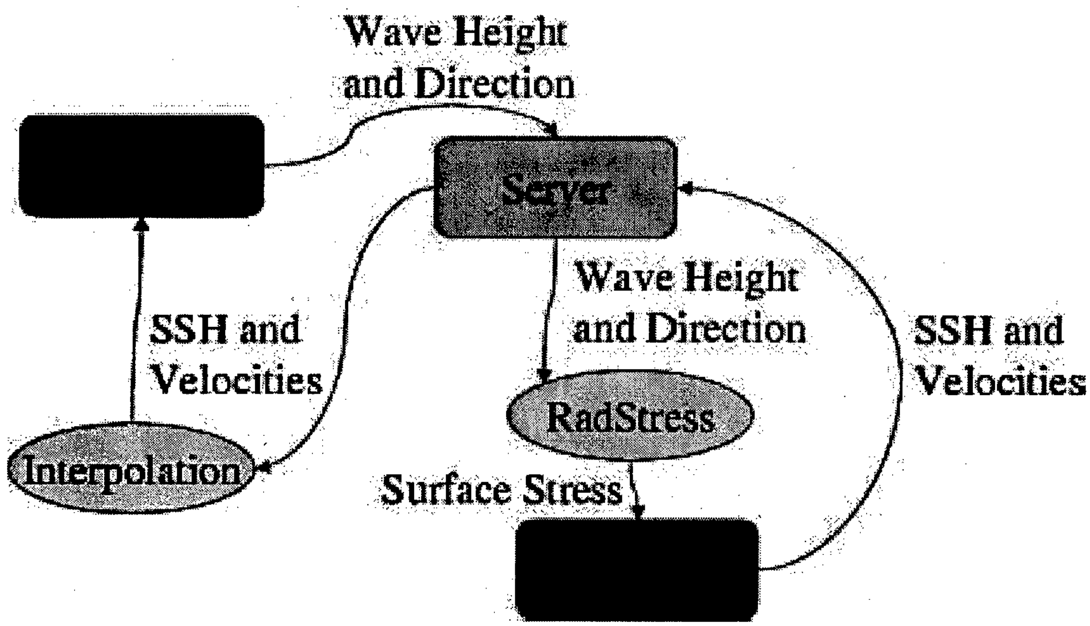

Figure 11. Example of how MCEL can be used to provide data between HFSoLE models.

In this example every box represents its own process, either numerical model, filter or the central server. This allows for an MDMP parallelization of the different models. Each model has its own pool of CPUs to work from which provides greater computational efficiency. This example was implemented for verification of the coupling scheme and it was shown that it provided a equivalent results to the traditional file I/O coupling scheme in half the time on a set of Linux workstations.

Acknowledgements

The HFSoLE Portfolio is funded by the High Performance Computing Modernization Office. The COAMPS wind fields utilized in the Adriatic study were performed by Dr. Jim Doyle (NRL-MRY) under the COAMPS 379 challenge project. The Adriatic NCOM simulations were performed by Dr. Julie Pullen (NRL-MRY) under the 379 challenge project. Special thanks to Dr. Tim Campbell and Dr. John Cazes (NAVO PET) who parallelized the serial SWAN code, CTA leaders Dr. William Burnett and Dr. Jeff Holland, and Dr. George Heburn (NAVO PET) for their support, and Ms. Margo Frommeyer for help with computer account coordination. The SeaWiFS image analysis was completed by the Ocean Optics Section, Code 7333 at NRL, courtesy of Dr. Richard Gould.

References

Blain, C. A., J. J. Westerink, and R. A. Luettich. 1994: The influence of domain size on the response characteristics of a hurricane storm surge model, *J. Geophys. Res.*, 99(C9):18467-18479.

Blain, C. A., 1998: Barotropic tidal and residual circulation in the Arabian Gulf, in Estuarine and Coastal Modeling, Proceedings of the 5th International Conference, M. L. Spaulding and A. F. Blumberg, eds., American Society of Civil Engineers, 166-180.

Blain, C. A., R. H. Preller, and A. P. Rivera, 2002: Tidal prediction using the Advanced Circulation Model (ADCIRC) and a relocatable PC-based system, Oceanography, 15(1), 77-87.

Booij, N., R.C. Ris and L.H. Holthuijsen, 1999: A third-generation wave model for coastal regions, Part 1, Model description and validation, J. Geophys. Res., 104(C4), 7649-7666.

Chao, S-Y., T. W. Kao, and K. R. Al-Hajri, 1992: A numerical investigation of circulation in the Arabian Gulf, J. Geophys. Res., 97(C7), 11219-11236.

Fortunato, A. B, A. M. Baptista, and R. A. Luettich, Jr., 1998: A Three-Dimensional Model of Tidal Currents at the Mouth of the Tagus Estuary, Cont. Shelf Res., 17(14):1689-1714.

Fox, D.N., W.J. Teague, C.N. Barron, M.R. Carnes and C.M. Lee, "The Modular Ocean Data Assimilation System (MODAS), 2002. Journal of Atmospheric and Oceanic Technology, Vol 19, pp 240-252.

Gailani, J., Lick, W., Ziegler, K. and Endicott, D., 1996. Development and calibration of a fine-grained-sediment transport model for the Buffalo River. J. Great Lakes Research, 22(3), 765-778.

Garratt, J. R., 1977: Review of Drag Coefficients over Oceans and Continents, Mon. Wea. Rev., 105, 915-929.

Glenn, S.M. and Grant, W.D., 1987. A suspended sediment stratification correction for combined wave and current flows. Journal of Geophysical Research, 92, 8244-8264.

Hodur, R. M. and J. D. Doyle, 1999. The Coupled Ocean/Atmosphere Mesoscale Prediction System (COAMPS), in Coastal Ocean Prediction, C. Mooers, ed., AGU, Washington, D. C., 125-155.

Hogan, T.F. and T.E. Rosmond, 1991, The Description of the U.S. Navy Operational Global Atmospheric Prediction System's Spectral Forecast Model. Mon. Wea. Rev., 119, 1786-1815.

Keen, T.R. and Glenn, S.M., 1998. Resuspension and advection of sediment during Hurricane Andrew on the Louisiana continental shelf, In: Spaulding and Cheng, R.T (eds.), Estuarine and Coastal Modeling V. American Society of Civil Engineers, pp. 481-494.

Keen, T.R. and Stavn, R.H., 2000. Developing a capability to forecast coastal ocean optics: Minerogenic scattering. In: Spaulding, M.L., and Butler, H.L. (eds.), Estuarine and Coastal Modeling VI. American Society of Civil Engineers, pp. 178-193.

Kinnmark, I.P.E. 1984. The Shallow Water Wave Equations: Formulation, Analysis and Application, Ph.D. Dissertation, Department of Civil Engineering, Princeton University.

LeProvost, C., M. L. Genco, F. Lyard, P. Vincent, and P. Canceil, 1994: Spectroscopy of the world ocean tides from a finite element hydrodynamic model, J. Geophys. Res., 99(C12), 24777-24798.

Luettich, R. A., J. J. Westerink, and N. W. Scheffner, 1992: ADCIRC: An advanced three-dimensional circulation model for shelves, coasts, and estuaries, Report 1: Theory and methodology of ADCIRC-2DDI and ADCIRC-3DL, Tech. Rep. DRP-92-6, Department of the Army, Washington, D. C.

Luettich, R.A. and J.J. Westerink, 1995: Continental shelf scale convergence studies with a barotropic model, Quantitative Skill Assessment for Coastal Ocean Models, Coastal and Estuarine Studies Vol. 47, American Geophysical Union, 349-371.

Luettich, Jr., R. A., J. L. Hench, C. W. Fulcher, F. E. Werner, B. O. Blanton, and J. H. Churchill, 1999: Barotropic tidal and wind-driven larval transport in the vicinity of a barrier island inlet. Fisheries Oceanography, 8 (Suppl. 2): 190-209.

Lynch, D.R. and W.G. Gray, 1979: A Wave equation model for finite element tidal computations, Comp. Fluids, 7, 207-228.

Martin, P.J., 2000, Description of the Navy Coastal Ocean Model, Version 1,0, NRL Formal Report 7322-00-9962. Nav. Res. Lab., Stennis Space Center, Miss., 45pp.

Naval Oceanographic Office (NAVOCEANO), 1997: "Data Base Description for Digital Bathymetric Data Base – Variable Resolution (DBDB-V), Version 1.0, Report, February, 1997.

Reynolds, R. M., 1993: Physical oceanography of the Gulf, Strait of Hormuz, Gulf of Oman-Results from the Mt. Mitchell Expedition, Marine Pollution Bulletin, 100, 35-59.

Rhodes, R.C., Hurlburt, H.E., Wallcraft, A.J., Barron, C.N. Martin, P.J., Metzger, E.J., Shriver, J.F., Ko, D.S., Smedstad, O.M., Cross, S.C., Kara. A.B., Navy Real-time Global Modeling Systems, 2002. Oceanography, Vol 15, No 1, pp 29-43.

Ross, D. A. and Stoffers, P., 1978. Report C: General data on bottom sediments including concentration of various elements and hydrocarbons in the Persian Gulf and Gulf of Oman. Technical Report to National Science Foundation. Unpublished Manuscript. Woods Hole Oceanographic Institution, Woods Hole, Massachusetts.

Smith, J. M. 2001. "Breaking in a Spectral Wave Model," Proceedings, Waves 2001, ASCE, 1022-1031.

Wallcraft, A.J., 1991: The Navy Layered Ocean Model user's guide, NOARL Report 35, Nav. Res. Lab, Stennis Space Center, Miss., 21pp.

Westerink, J. J., R. A. Luettich, J. Muccino, 1994: Modeling tides in the Western North Atlantic using unstructured graded grids, Tellus, 46a(2), 178-199.